United Technologies Research Center

Isaac Cohen, Claudio Pinello, Alessandro Pinto, Alison Gotkin

Jun. 18, 2015

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United Technologies

Business units

UTC Building & Industrial Systems

Otis

UTC Climate, Controls & Security

Sikorsky

Pratt & Whitney

UTC Aerospace Systems

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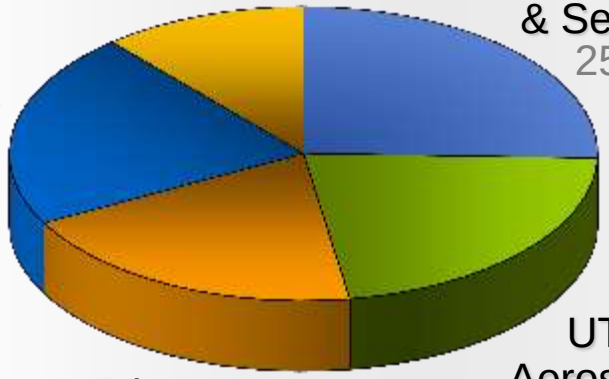
United Technologies

2014 Sales: $65.1 billion

UTC invested $4.8B in 2014 on company and customer funded R&D

Business unit sales…

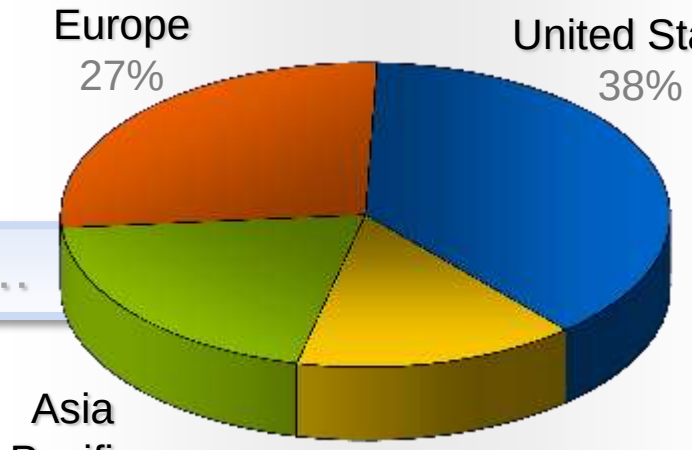


Segment…

45% Commercial & Industrial

55% Aerospace

Geographic sales…



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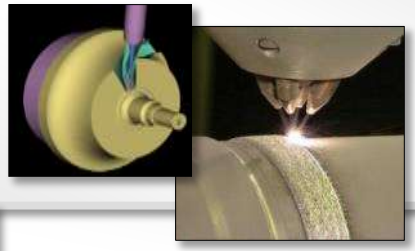
UTRC…UTC's Innovation Engine

Defining what's next

Define new frontiers…

AIS
Autonomous
& intelligent systems

Advanced manufacturing



Big data

Co-develop new technologies…

Next Gen
centrifugal

GTF
lubrication

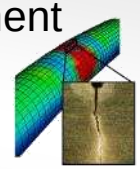
Solve tough problems…

Materials
characterization

Surface topology
and wear analysis

Measurement
science

Digital imaging
strain analysis



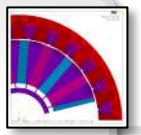
Failure
analysis

Scattering
to measure
residual stress

Serve as hub for technical interchange…

Tech
scouting

Rare
Earth
Magnets



REM
workshops

Leverage global network of innovation…

Monetize UTC intellectual property…

Alternative
markets

New
business models

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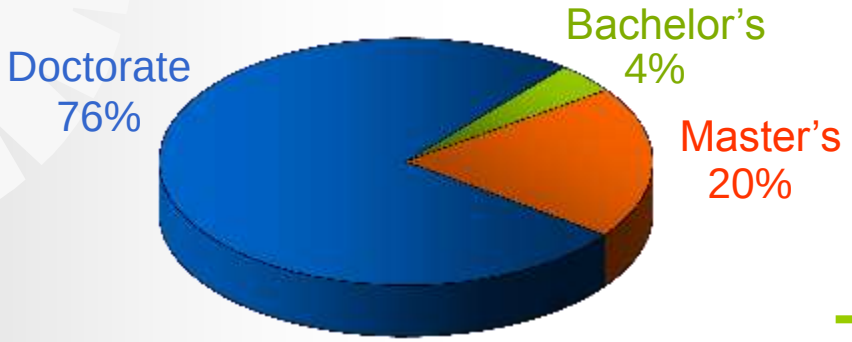
Our People…

96% of our technical staff have advanced degrees



. . . education

global diversity…

~ 600 employees representing approximately 40 different countries

More than 400 technical employees; 76% hold Ph.D.s

excellence in innovation

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UTRC Organization

David Parekh
Vice President, Research, and Director, UTRC

Jim Fritz
Director, Operations

Business Services

Gary Linsey
Business Development

Phil Podgorski
Finance

Sue Gilbert
Human Resources

Greg Stephenson
Law

Program Offices

Mark Thompson
Otis

Greg Tillman
(Acting)
Pratt & Whitney

Andrzej Banaszuk
Sikorsky

Steve Tongue
UTC Aerospace Systems

Craig Walker
UTC Climate, Controls & Security

John Milton-Benoit
Manufacturing & Service Technologies

Departments

Jodi Vecchiarelli
Physical Sciences

Isaac Cohen
Systems

Paul Van Slooten
(Acting)
Thermal & Fluid Sciences

International

Murilo Bonilha
UTRC China

Stevo Mijanovic
UTRC Ireland

Senior Fellows

Vlado Blasko

Sergei Burlatsky

Mike Francis

Joe Sangiovanni

Om Sharma

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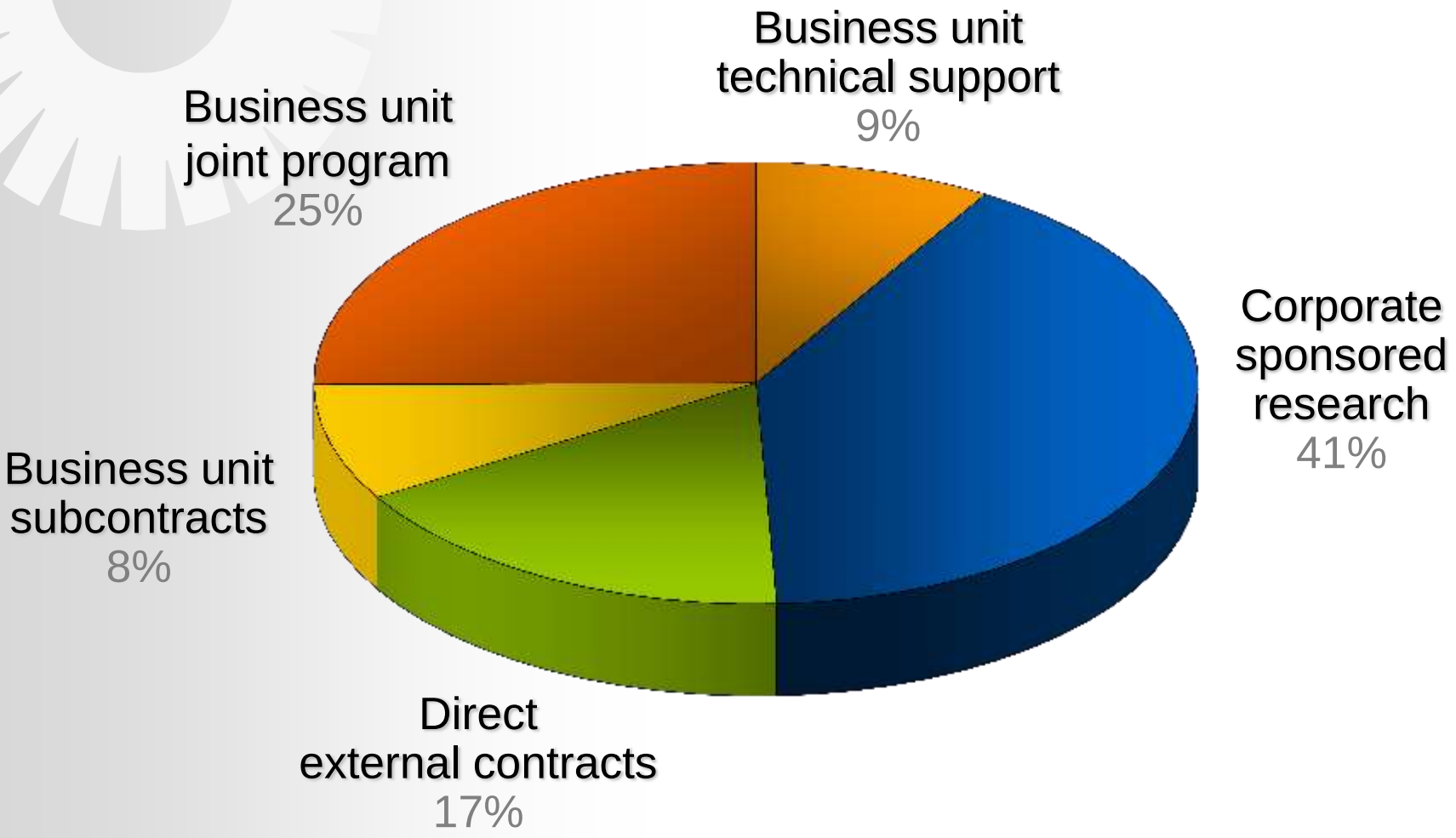
Source of Funding



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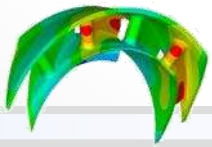
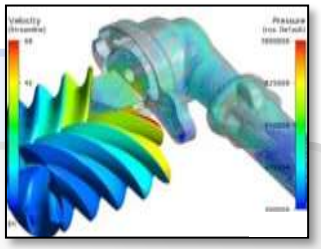
Department Capabilities

Physical Sciences…

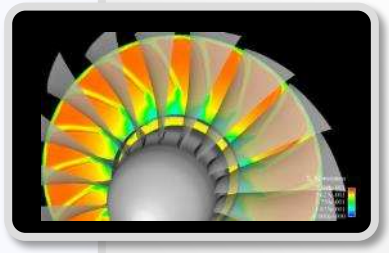
- Applied physics
- Advanced materials
- Measurement science
- Chemistry
- Mechanics

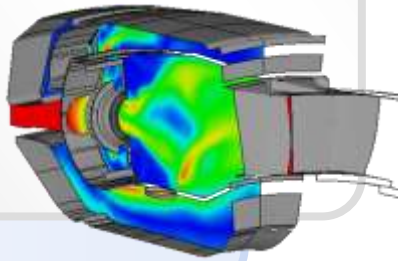


Thermal & Fluid Sciences…



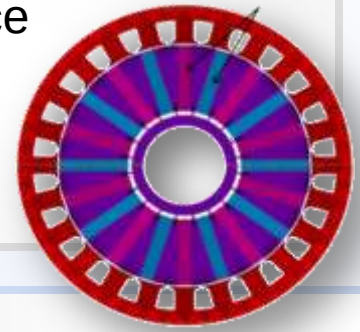
- Acoustics
- Aerodynamics
- Combustion
- Applied fluid dynamics
- Thermal management





Systems…

- Cyber physical systems
- Dynamical systems and control
- Embedded intelligence
- Decision support
- Power electronics



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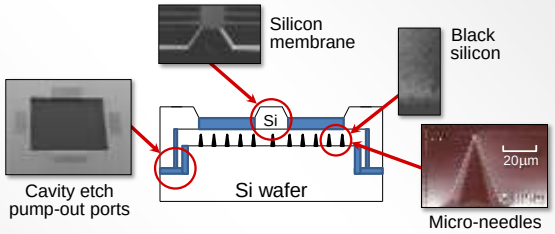
Physical Sciences Department

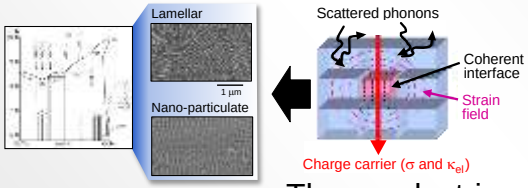
Applied Physics

Optical and chemical sensors, thermoelectrics, and NEMS



NEMS-based device

NEMS: Nanoelectromechanical systems



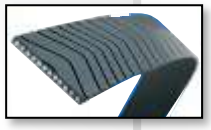
Thermoelectrics

Advanced Materials

Structures and coatings

Si_3N_4 turbine components

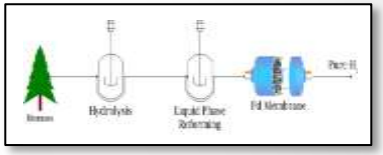
Otis coated steel belt



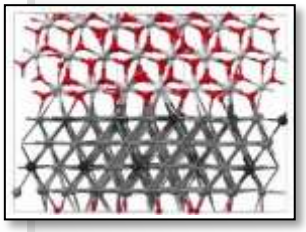
Composites

Environmental Science Materials Chemistry

Material synthesis, catalysts and computational chemistry

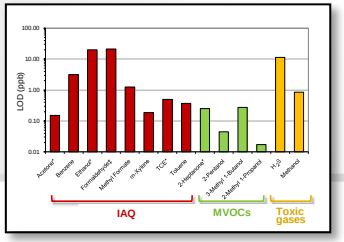


Chemical process development



Computational chemistry

Air quality analysis and control



Measurement Science

State-of-the-art analysis

Mechanical behavior

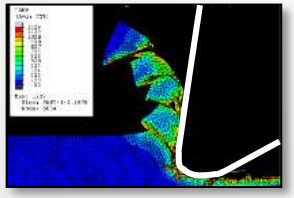
Surface spectroscopy

FIB microscopy

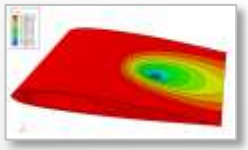
Focused Ion Beam

Solid and Surface Mechanics

Structural analysis and material damage modeling



Physics-based manufacturing



Blade after impact

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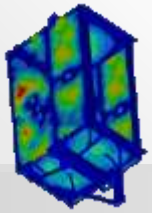
Systems Department

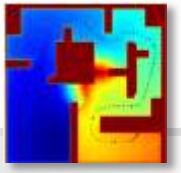
System Dynamics & Optimization

- Uncertainty quantification and propagation
- Multi-scale system modeling
- Mathematics on graphs, computational mathematics



Topology optimization

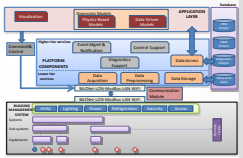
Path planning



Embedded Systems & Networks

- Software engineering
- Scalable hardware and software architectures
- Communications, wireless and energy harvesting

Building services platform

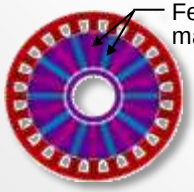


Wireless communication and controls

Power Electronics

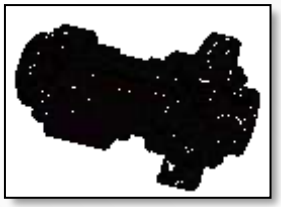
- High density converters
- High temperature-high frequency devices
- Converter topologies
- Low REM machine design

Universal power module: Power Brick



Ferrite magnets

Otis GreenPower Machine



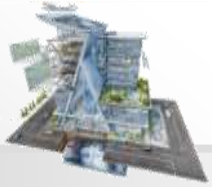
5-D magnetic bearings

REM – rare earth materials

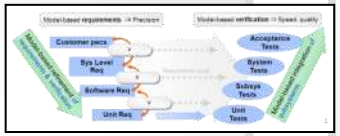
Control Systems

- Adaptive, multi-variable and predictive controls
- Control in presence of uncertainty
- Data driven adaptive controls

Model predictive control for HVAC



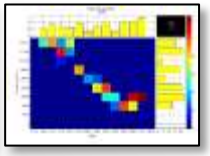
Cyber Physical Systems



- Formal methods, verification and validation, code synthesis
- Embedded Intelligence
- Advanced planning and reasoning

Decision Support & Machine Intelligence

- Data-based models, data mining, machine learning
- Diagnostics, prognostics, PHM
- Sensor fusion
- Human machine interaction



Building diagnostics

PHM for gearbox

PHM – prognostics and health management

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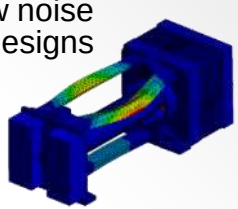
Thermal & Fluid Sciences Department

Acoustics

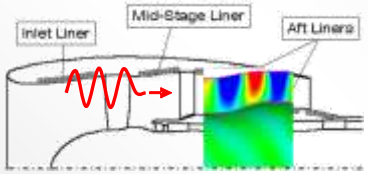
Noise and vibration diagnostics, modeling, and control

Low noise designs



N&V diagnostics

High fidelity computational modeling

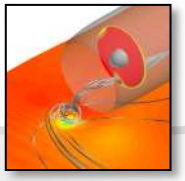


Aerodynamics

Fluid mechanics of gaseous flows

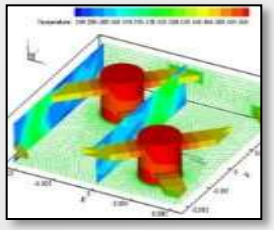
Applied aerodynamics

Computational fluid dynamics

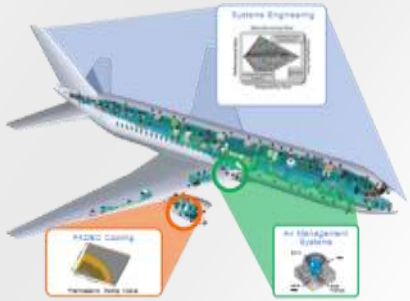


Thermal Fluid Dynamics and Thermal Management

Energy recovery



Heat and mass transfer

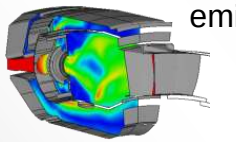


System analysis and optimization

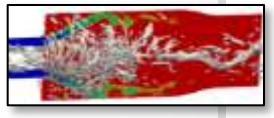
Combustion

Dynamics and chemistry of reactive, multi-phase flows

Performance and emissions



Fire suppression



Dynamics

Sprays

High speed propulsion

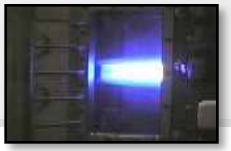
Aero-thermal Testing

Experimental model validation and component performance

Aerodynamics

Spray characterization

High and low Mn combustion



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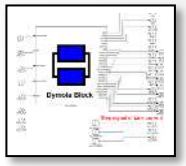
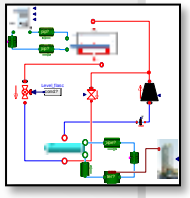
UTRC China Capabilities and Research Areas

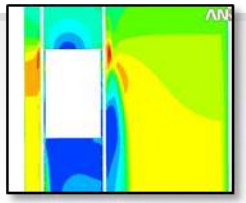
Thermal and Building Systems

- Thermo-fluid systems dynamic modeling
- Environmentally friendly refrigerants and cycles
- Integrated building/HVAC modeling
- Building diagnostics

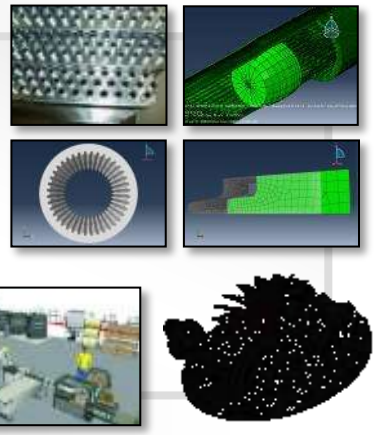
Fluid Dynamics

- Turbo-machinery design and analysis
- HVAC component optimization
- Building air/reactive flow modeling
- UTCFD applications



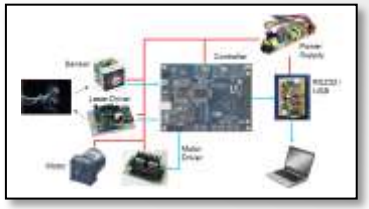
Mechanical Systems

- Solid mechanics
- Finite element modeling
- Machining modeling
- Supply chain optimization



Decision and Control Systems

- Video analytics
- Data mining
- Controls
- Embedded systems
- Software engineering

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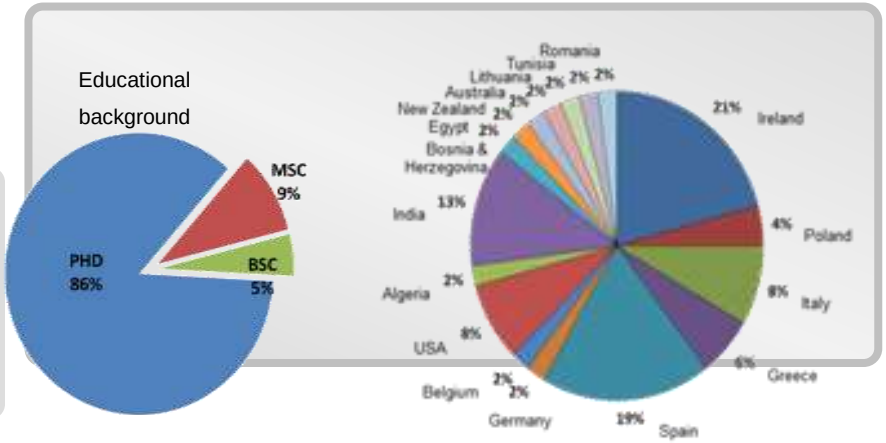
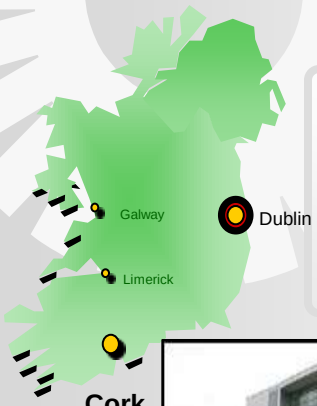
UTRC Ireland

Est. 2010 in Cork

Highly skilled and diverse workforce





Objectives…

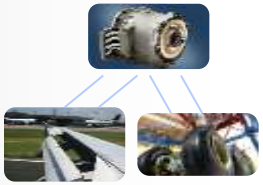
Hub for European interactions

Leverage European talent and investments opportunities in ICT

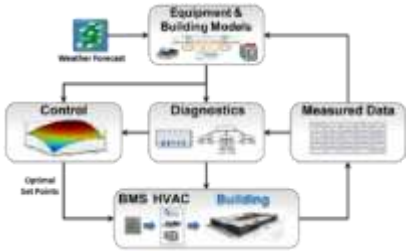
Support commercial & aerospace UTC BUs

Technical capabilities and Groups

System Modelling & Power Electronics



Controls & Decision Support



Networks & Embedded Systems

Network of national and EU resources

Insight – Centre for Data Analytics

SFI – Research Centres

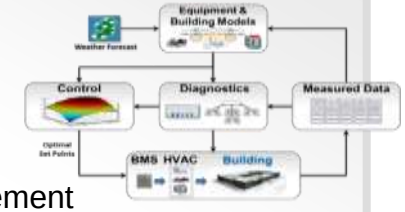
Lero – Software Engineering Research Centre

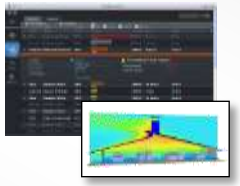
Connect – Communication Networks Research Centre

Technical Capabilities

Controls & Decision support

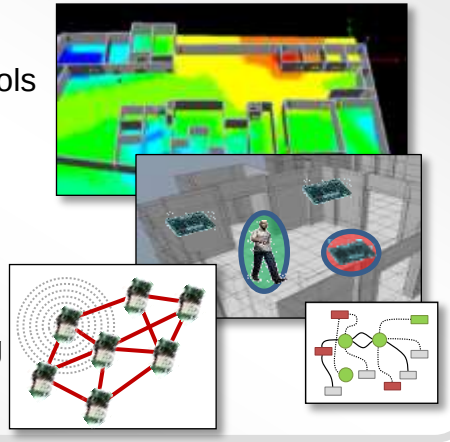
- Model-based control design
- Optimization-based control
- Fault detection and diagnostics
- Data analytics for alarm management
- Data- and physics-based diagnostics
- Thermal system modeling
- Video analytics





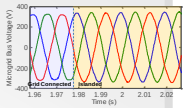
Networks & Embedded Systems

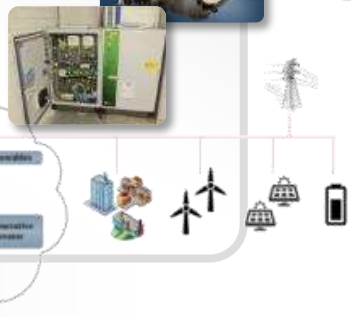
- Sensor networks
- Communications protocols
- Model-based design
- Formal methods
- Embedded systems
- Software engineering
- Constraint programming



Power Electronics

- Hierarchical system modeling and controls
- Model-based power converter design
- Electric motor optimization
- Digital control of converters & drives
- Power quality analysis
- Grid estimation & emulation
- HiL / rapid prototyping





EU R&D Framework

Early impact on R&D programs through memberships and networks

UTRC Ireland

United Technologies Research Center

Memberships and networks

- **European Organisation for Security**
- **Energy Efficient Buildings Association**
- **Smart Energy Demand Coalition**
- **Smart Cities Stakeholder Platform**
- **Ireland National Contact Points** (ICT, Energy, Security, Aerospace, NMP)
- **UTIO Brussels**
- **Artemis-IA**

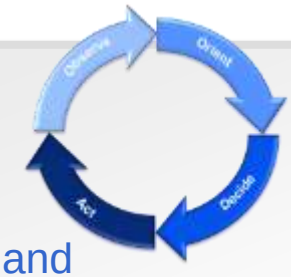
Impact

- EU Legislation
- EU Research Strategy
- Industry Roadmaps
- R&D Programs
- Funding Call Texts
- Consortium Formation

Key Initiatives

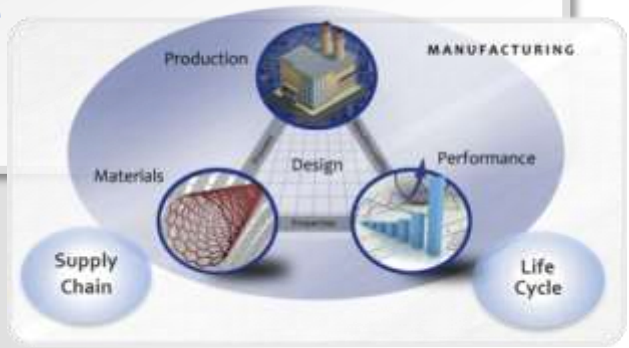
Autonomy

Advancing software architecture, and perception for collaborative autonomous platforms



Advanced Manufacturing

Reinventing design space for new material design, process, manufacturability, logistics, and life cycle



Service Technologies

Human-centered design
Cloud-based analytics
Cyber-physical security

This page contains no technical data subject to the EAR or the ITAR.

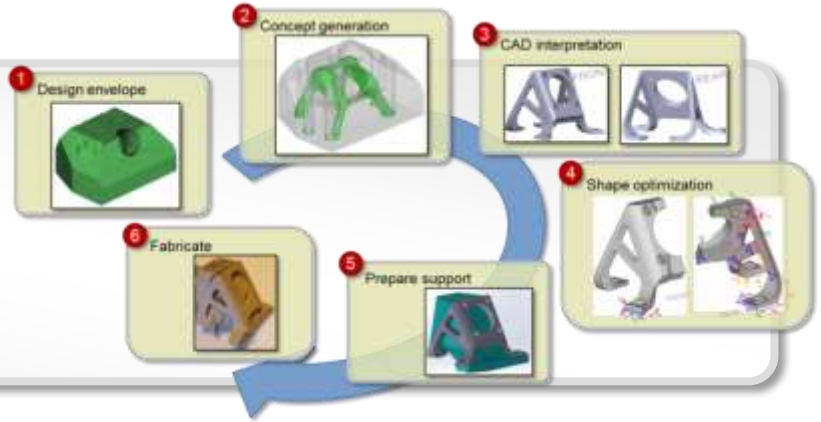
Advanced Manufacturing

Topology Optimization

Topology Optimized Design Methodology for Additive Manufacturing

Current part design:
- **uneven stress distribution**
- **premature failure**

Final design:
- **75% reduction in stress**
- **20% reduction in weight**

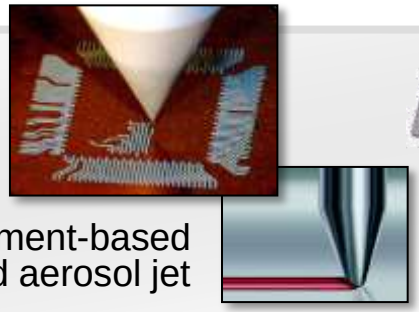


Cold Spray

- Superior material properties
- Highest deposition rates
- Multiple material deposition
- Limited to line-of-sight processing
- Lower geometric fidelity

Direct Write

- Potential for wide variety of geometries
- Excellent resolution depending on technique
- Functional materials primary focus
- Multiple material deposition



Filament-based and aerosol jet

Actuators, motors and MEMS

Sensors and arrays

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The Role of Autonomy

State-of-the-art in autonomy to mission/operational-level capabilities

internal

- Diverse, multi-disciplinary skills
- Culture of collaboration

World class expertise and leading-edge ideas

external

Carnegie Mellon

Penn

MIT

Georgia Institute of Technology

Integration and validation

- Hardware-in-the-loop simulation
- Human machine interaction

HiLSIM

HMI

Rapid prototyping

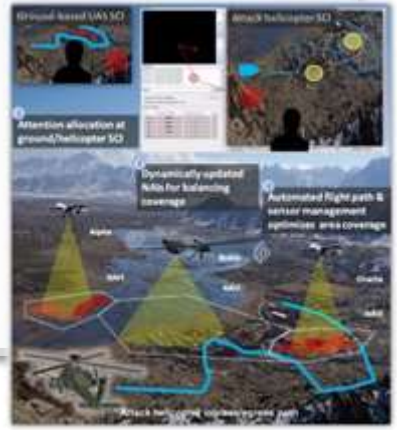
- Low cost flight research
- Individual algorithm assessment
- Heterogeneous platforms

Flight test

OPV / UAS

- Optionally piloted vehicle/ unmanned aircraft systems demonstrator
- Rapid software mods
- Validate, verify and certification

Revolutionary products and services with trusted autonomy



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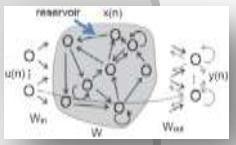
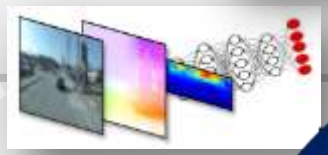
Service Technologies Initiative

Analytics/Big Data

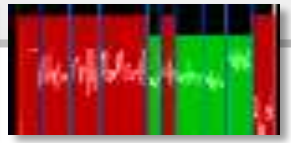
- Scalable algorithms and data management
- Distributed analytics (cloud, GPU)
- Data fusion



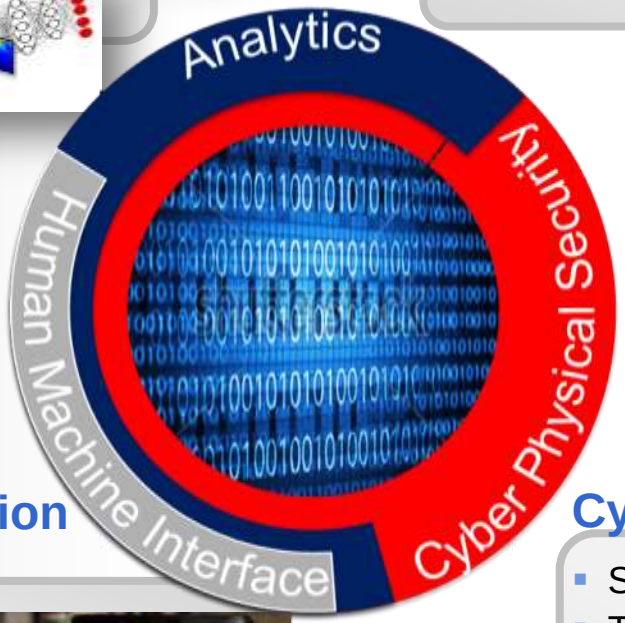


Decision support and integration

- Analytics to Action: Policy Mapping
- Robust scalable architecture
- Integrated Analytics / HMI optimized tool chain



Interactive machine learning-learning experts' knowledge

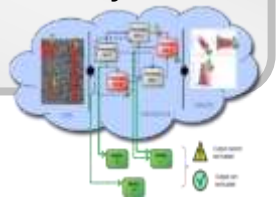


Human Machine Interaction / User Experience

- User-centered design
- Adaptive user interfaces
- Augmented reality for field operators

Cyber Physical Security

- Secure Software
- Trusted and secure embedded systems
- Trusted Service and Privacy



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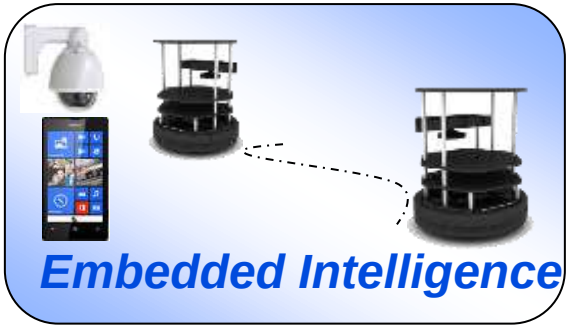
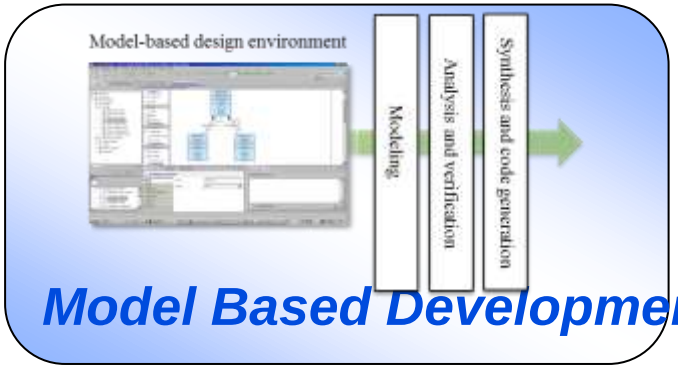
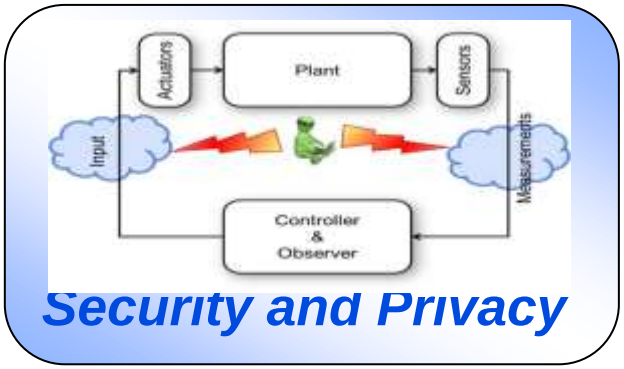
Cyber-Physical Systems Group

- Enabling Predictable Design and Reliable Operation of Intelligent Systems-of-Systems
  - Embedded Intelligence, advanced reasoning
  - Perception and robotics
  - Model-Based Design and Verification: languages, design and analysis tools
  - Security & Privacy

- Key technical activities
  - Requirements Analysis
  - Contract-Based Design
  - Distributed Intelligent Agents
  - Sequential Decision Making
  - Security & Privacy in distributed and cloud-based systems







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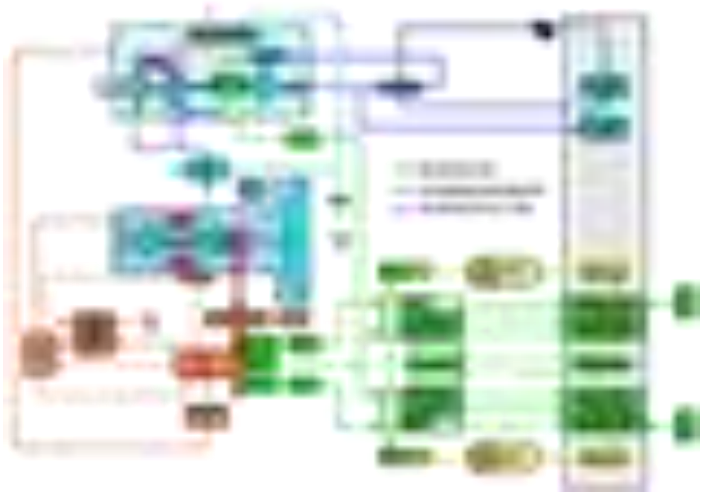
UTC Complex Systems

Integrated Building Systems

Aerospace



Autonomy

- Heterogeneous systems
- Designed by different organizations
- Operated by different organizations
- Corresponding Human-Machine Integration challenges
- Different key performance indexes and cost points

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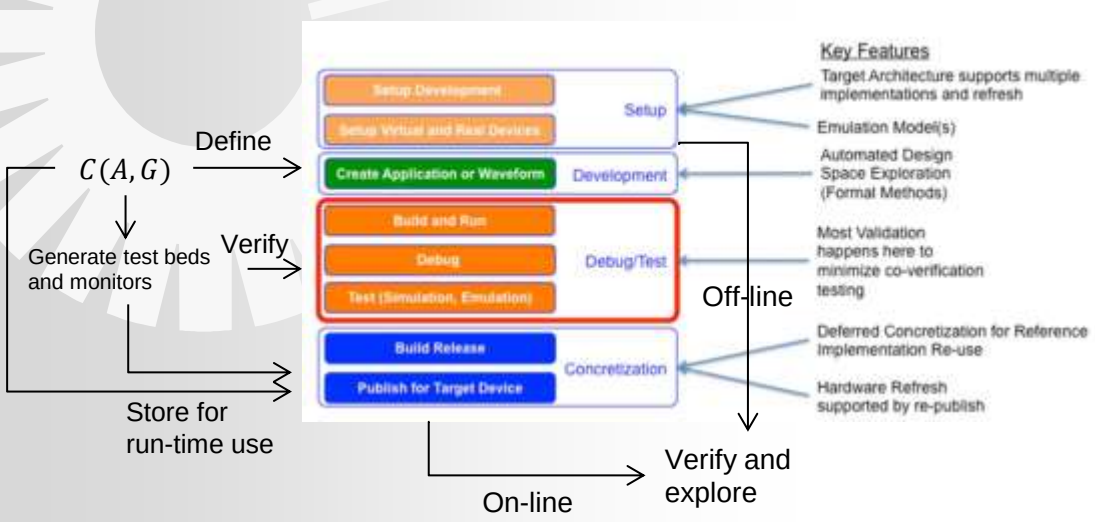
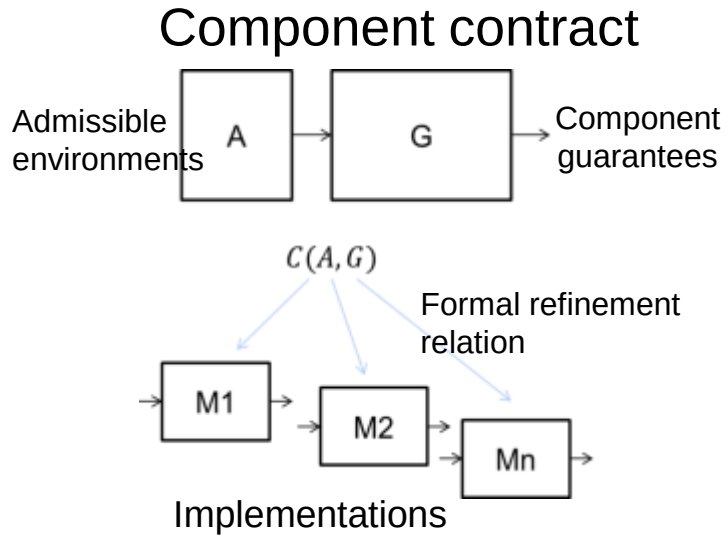
Communication in Contested Environments

Contract-based development and deployment of communication systems





Phase 1 : Language definition for static interfaces; editors; ontology and templates for C2E application; integration with the rest of the development environment; verification and generation of monitors/test bed.

Phase 2 : Run-time services for discovery, negotiation and reconfiguration

Phase 3 : Language extension for dynamic interfaces (state machines); verification and monitor/test bed generation; Design space exploration tools

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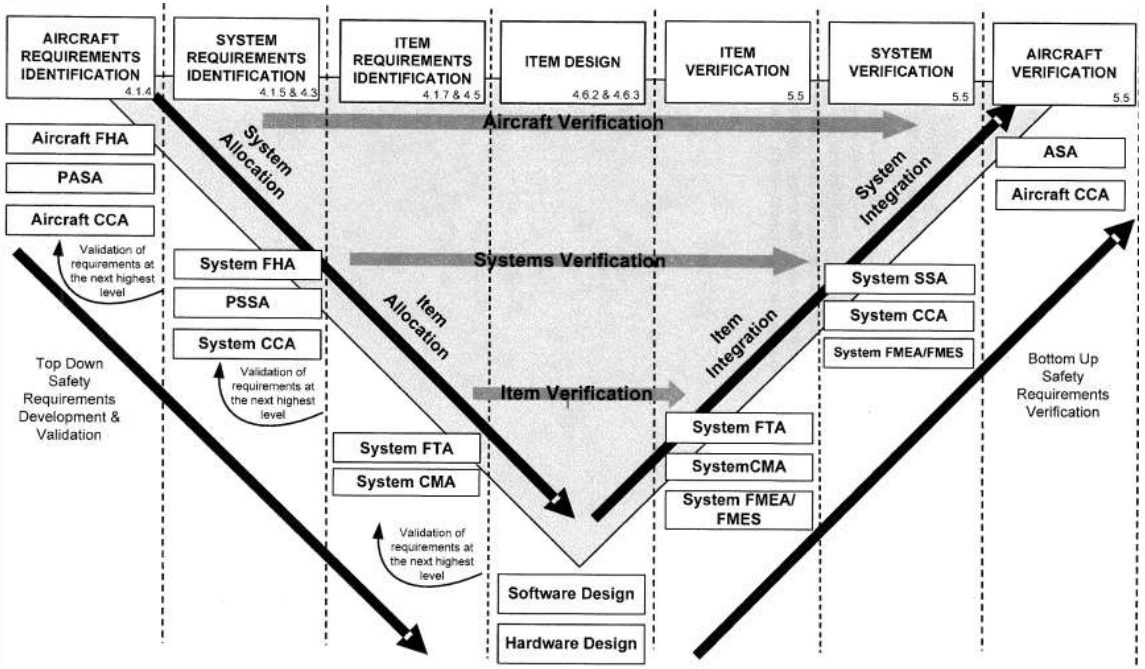
Validation and Verification

- Verification: Are we building the system right?
  - Can start when some design items are available
  - Traditionally in full-force when most items are available
- Validation: Are we building the right system?
  - Can start when requirements are forming

ARP4754A and DO-178C Processes



- The cost to discover and correct a requirement (or design) problem increases dramatically in later stages of design

Claudio Pinello, Cong Liu, Eelco Scholte, Alberto Ferrari, “First things first: a case for rigorous requirements analysis”, invited panel talk ESWEEK 2013

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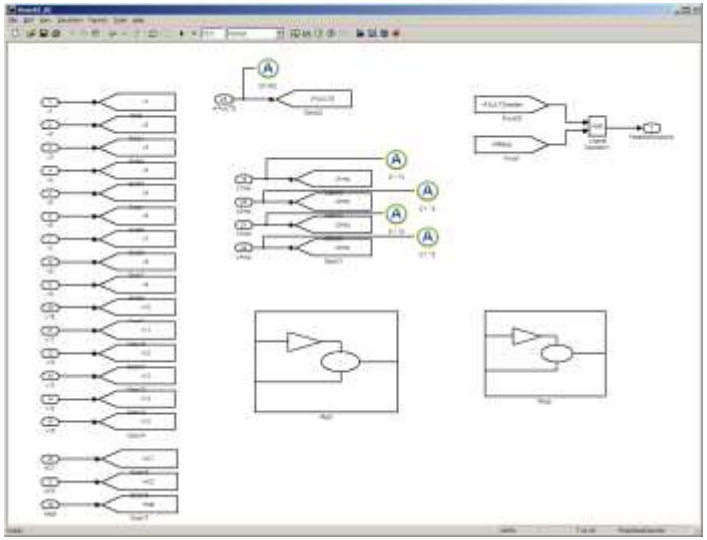
Model Based Design and Requirements Analysis

From natural language to models



- Model the plant + control structure, enough detail to state requirements precisely, not more.
- Model the requirements as constraints on the control variables
- Resist temptation to model the solution (operational models)
  - Might mask requirements conflicts, might implicitly fill-in missing assumptions, etc…
- Examples:
  - Heating and Cooling shall not be provided simultaneously to the same zone: NOT (z2.heated AND z2.cooled)
  - Zone z1 shall never be heated: NOT z1.heated
- Ambiguity: does “heated” include heat from adjacent zones? If so, how many “hops” count? How about “fresh air”?
  - Formalization forces disambiguation

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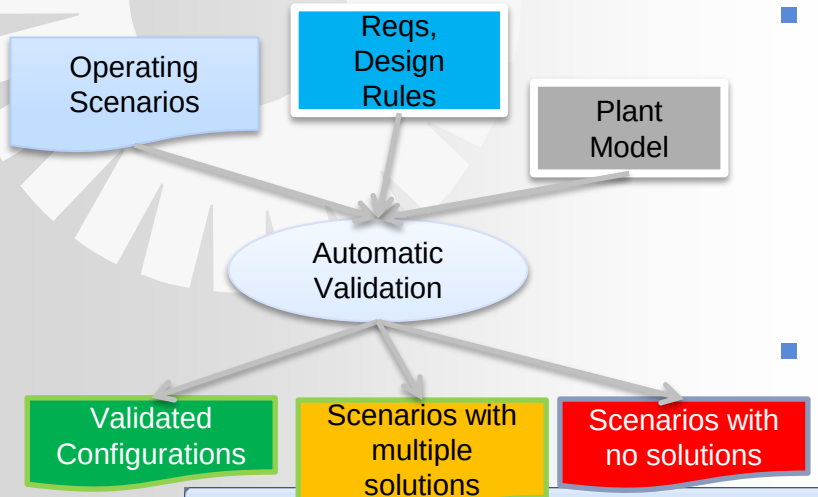
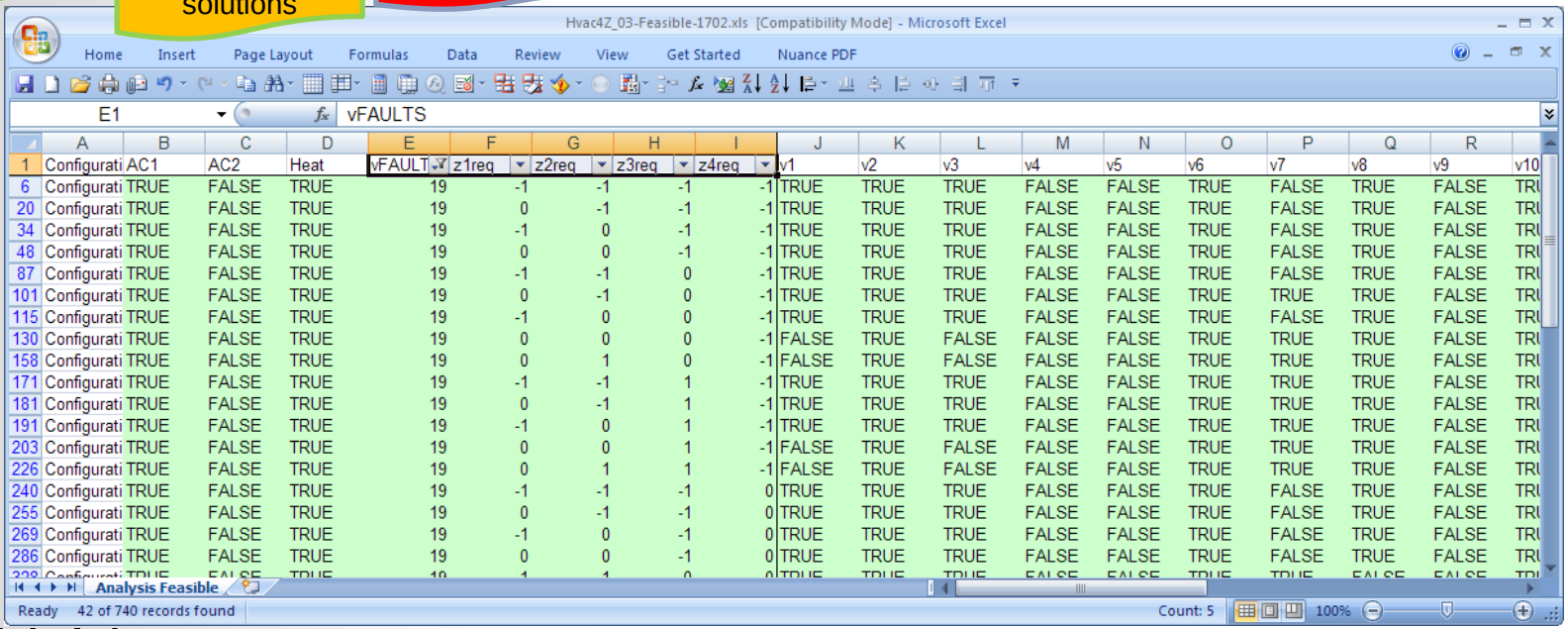
Consistency and Determinism Analysis

Validating the requirements



- Ask: does there exist at least one actuator solution for each possible input request?
  - No solution ➔ conflicting requirements or insufficient plant redundancy
  - Multiple solutions ➔ possible under-specification
- Leverage Simulink verification frameworks, e.g. FormalSpecs Verifier (UTSCE/ALES)



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6	Configurati	TRUE	FALSE	TRUE	19	-1	-1	-1	-1	TRUE	TRUE	TRUE	FALSE	FALSE	TRUE	FALSE	TRUE	FALSE	TRU
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Design Methods, Architectures, Tools and Algorithms for AIS

AUTONOMOUS AND INTELLIGENT SYSTEMS

United Technologies Research Center

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Autonomous Intelligent Systems:

From following instructions to achieving goals

- To be useful, intelligent systems need to accommodate high-level declarative objectives
  - "Search Zone A for intruders" vs

    "Move to (19.23, 89.97); scan-thermal; Move to (19.95, 92.42); detect motion;…"
  - "Direct people to theater exits" vs

    "activate signage XY; if main_hall_crowded, activate signage XZ; dispatch elevator…"
  - "Do my laundry" vs

    "Pick sock at (2,3,1); Place into basket at (12,3,1), …"
  - "Deliver supplies to ship XY, while avoiding threats"

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Sequential Decision Making: Example

Initial state

Actions (with models of effects):

- Open, close washer
- Move to table, laundry area
- Pick, place clothes/basket
- Locate clothes (vision)

Feasible/optimal sequence?

Goal state

- Agent needs to deal with uncertainty in
  - Observations: Cannot detect exact number of dirty clothes in a heap,
  - Action effects: Pinch grasp results in picking an unknown number of clothes
- Behavior not prescribed; needs to be computed and executed

- Distributed agents need to exchange knowledge, objectives, and plans. And need to coordinate executions. Need to gracefully update plans when resources and agents are added/removed.

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SYSTEM-THEORETIC METHODS FOR SECURE CONTROL OR COMPUTATION

United Technologies Research Center

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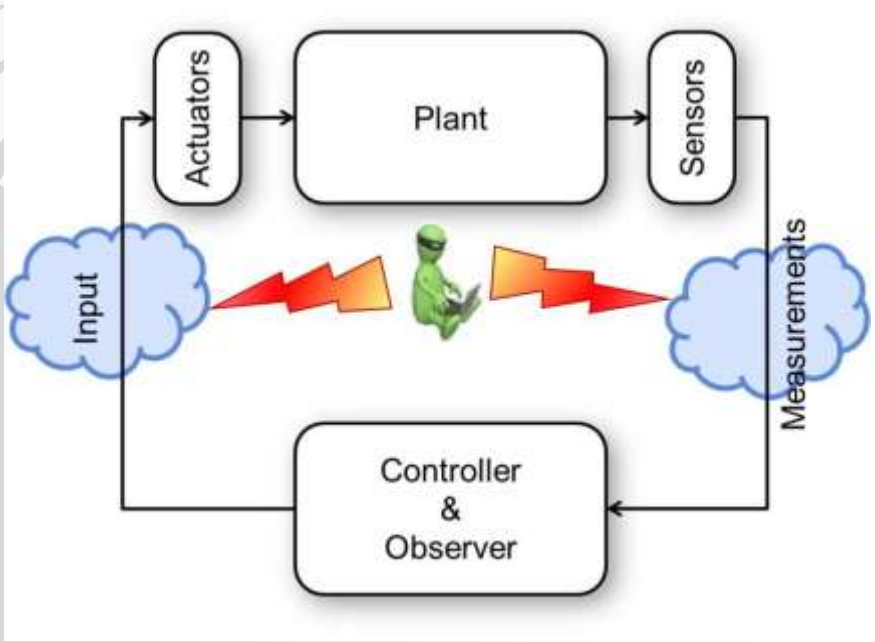
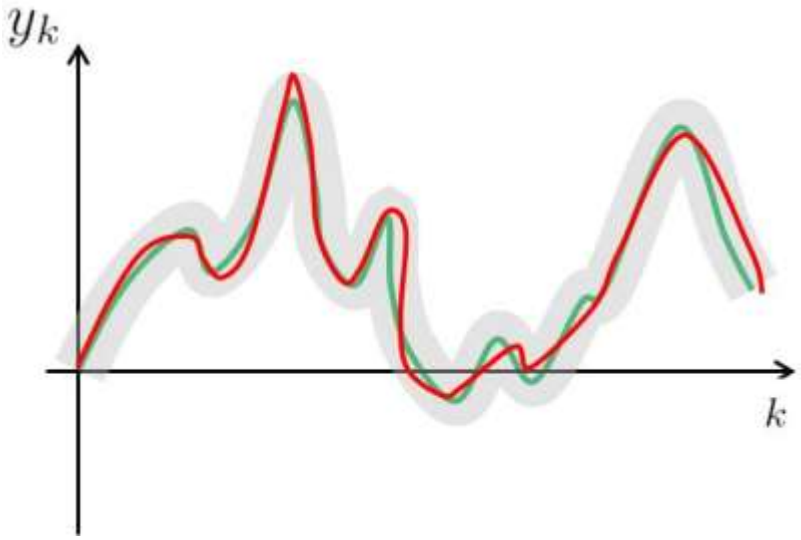
Motivation (I): Secure Control

Stealth Attack: Coordinated manipulation of inputs and measurements





Classic cases: Stuxnet, Water Network in Australia, Tram system in Poland

Design principles to deny existence of/reveal stealth attacks

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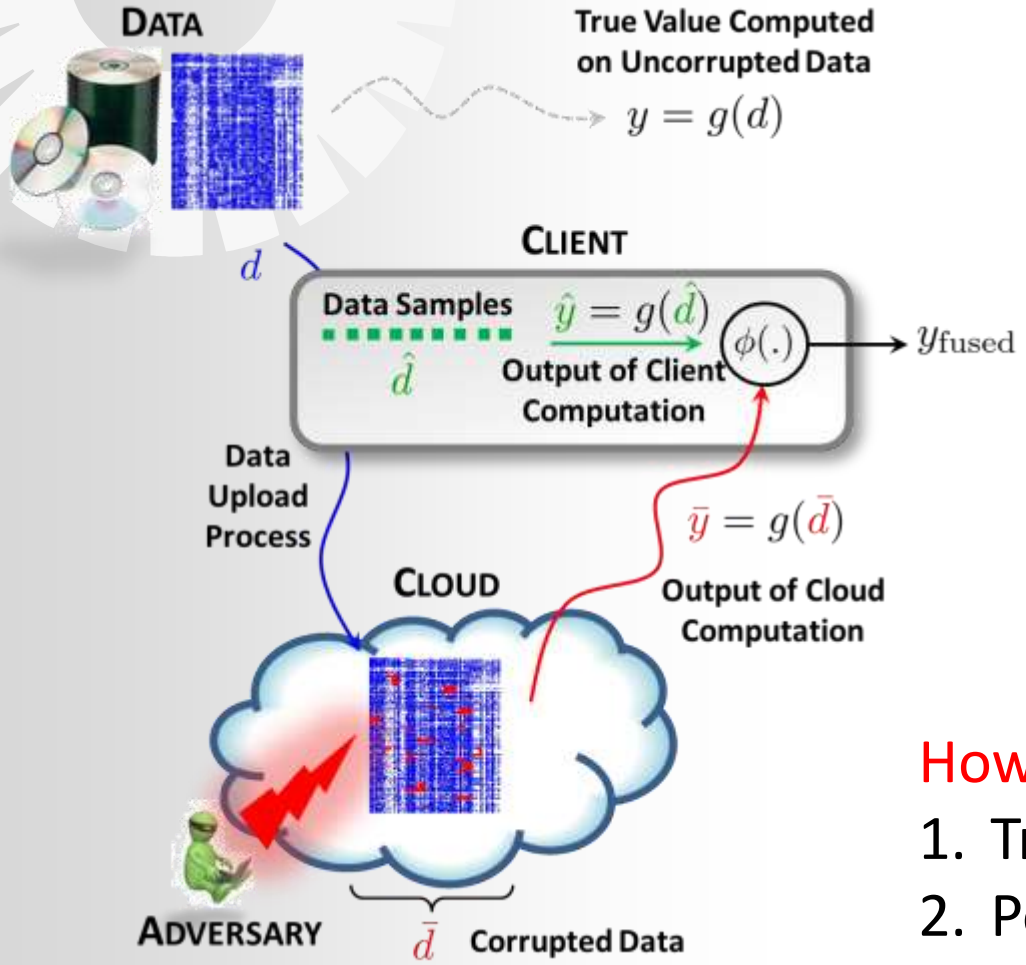
Motivation (II): Trusted Computation



How to balance:

1. Trusted but approximate value
2. Possibly Poisoned Cloud Output

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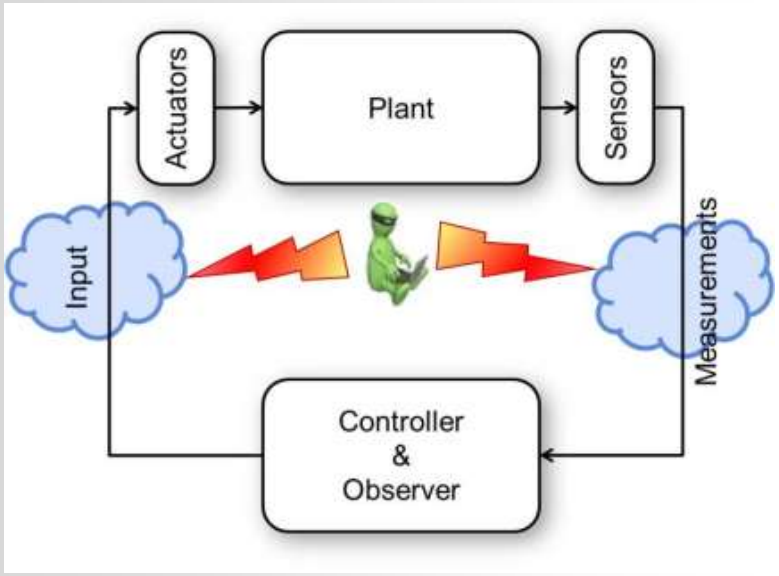
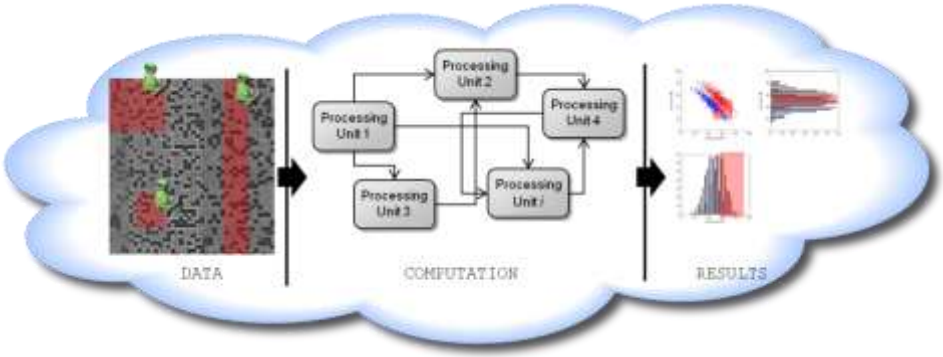
Practical Considerations

- Legacy Systems
- Lack of Attacker Models
- Attack Likelihood versus Impact





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Guiding Principles…

- UTC and its business units are our primary customers.
- We deliver on our promises yet are willing to take risks on ideas.
- Research is our core business, from discovery to demonstration.
- Our role is to deliver technology options, not new products.
- Technical excellence AND business impact is our objective.
- Agility is our hallmark; the world will continue to change.
- Our people are our *primary asset; it is all about talent.*

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